Int J Life Cycle Assess (2014) 19:872–881
DOI 10.1007/s11367-013-0676-z

Surplus cost as a life cycle impact indicator for fossil resource scarcity

Thomas C. Ponsioen · Marisa D. M. Vieira · Mark J. Goedkoop

Received: 23 July 2013 / Accepted: 24 November 2013 / Published online: 20 December 2013

Abstract
Purpose In life cycle impact assessment, various proposals have been made on how to characterise fossil resource scarcity, but they lack appropriateness or completeness. In this paper, we propose a method to assess fossil resource scarcity based on surplus cost, which is the global future cost increase due to marginal fossil resource used in the life cycle of products.
Methods The marginal cost increase (MCI in US dollars in the year 2008 per kilogram per kilogram produced) is calculated as an intermediate parameter for crude oil, natural gas and coal separately. Its calculations are based on production cost and cumulative future production per production technique or country. The surplus cost (SC in US dollars in the year 2008 per kilogram) is calculated as an indicator for fossil resource scarcity. The SC follows three different societal perspectives used to differentiate the subjective choices regarding discounting and future production scenarios.
Results and discussion The hierarchist perspective SCs of crude oil, natural gas, and coal are 2.9, 1.5, and 0.033 US$_{2008}$/GJ, respectively. The ratios between the indicators of the different types of fossil resources (crude oil/natural gas/coal) are rather constant, except in the egalitarian perspective, where contrastingly no discounting is applied (egalitarian 100:47:21; hierarchist 100:53:1.1; individualist 100:34:0.6). The ratio of the MCIs (100:48:1.0) are similar to the individualist and hierarchist SC ratios.
Conclusions In all perspectives, coal has a much lower resource scarcity impact factor per gigajoule and crude oil has the highest. In absolute terms of costs per heating value (US dollars in the year 2008 per gigajoule), there are large differences between the SCs for each perspective (egalitarian > hierarchist > individualist).

Keywords Characterisation factors · Cultural theory · Fossil resources · Life cycle impact assessment · Marginal cost increase · Surplus cost

Abbreviations

CF	Characterisation factor
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
MCI	Marginal cost increase
SC	Surplus cost

1 Introduction

Life cycle assessment (LCA) is a methodology that helps assess and improve the environmental profile of goods and services, considering their entire life cycle. This comprises all activities from raw material extraction, through manufacturing, use, and end-of-life waste disposal. Life cycle impact assessment (LCIA) constitutes an important phase of an LCA study where impacts are quantified on the basis of life cycle impact indicators. An impact indicator can be defined anywhere along the cause–effect pathway from the extraction of natural resources and release of emissions to the damage caused. In LCIA, the damage caused is often grouped in three areas of protection, also named as safeguard subjects: human health, natural environment, and natural resources (Jolliet et al. 2004). The first two areas of protection are relatively well established, but there is no consensus regarding

Responsible editor: Göran Finnveden

Electronic supplementary material The online version of this article (doi:10.1007/s11367-013-0676-z) contains supplementary material, which is available to authorized users.

T. C. Ponsioen (✉) · M. D. M. Vieira · M. J. Goedkoop
PRé Consultants BV, Stationsplein 121, Amersfoort 3818 LE, The Netherlands
e-mail: ponsioen@pre-sustainability.com

the issue of concern related to natural resources (EC-JRC-IES 2011), even though resource use (particularly land and fossil resources) is often an important driver of overall environmental impact in the life cycle of products (Huijbregts et al. 2008).

Environmental pollution due to fossil resources combustion, such as climate change and acidification, receives a lot of attention because of our increasingly energy-intensive lifestyle (Lenzen et al. 2004; Jackson and Papathanasopoulou 2008). In addition, society's concern about a limited supply of fossil resources is increasing. Recently, the fast economic growth of emerging economies, in particular, China and India, has led to an energy demand larger than ever. As a result, crude oil, natural gas and coal have become ever more important energy sources (BGR 2010). However, there is a near-term rapid decline in conventional oil production, a relatively small contribution from non-conventional oils, and a predicted decline in conventional gas production in the near future (Bentley 2002; BGR 2010).

In the past, several types of LCIA methods were developed to assess the impact of fossil resource use, each describing different effects (Lindeijer et al. 2002; Jolliet et al. 2004; Finnveden 2005; Stewart and Weidema 2005; Berger and Finkbeiner 2011; EC-JRC-IES 2011). LCIA methods measuring fossil resource use can be categorised into three main categories based on the following: (1) inherent properties, (2) use/stock ratio, and (3) increased efforts. Methods included in the first category focus on inherent properties of fossil resources, such as mass or energy and entropy. However, the relevance of this approach in the LCA context is questionable because the impact factor is the same regardless of how much of a resource is still available for extraction. Methods in the second category, based on use/stock ratios, give an indication of the rate at which different resources are depleted as well as an estimate for how long they may last with present-day technology and demand. This concept has been used widely in LCIA methods (Guinée et al. 2002; Hauschild and Potting 2005; Schneider et al. 2011). Methods that belong to the third and last category describe the future consequences of current resource extraction based on the concept that extracting easier resources now means that in the future (lower quality) resources need to be extracted under more challenging conditions and with alternative technologies. The additional efforts that are required can be described by higher energy requirements or additional costs (Müller-Wenk 1998; Steen 2006; Goedkoop and De Schryver 2009).

Van der Voet (2013) defined depletion of a resource as a reduction of its geological/natural stocks on Earth and defined scarcity as an insufficiency of resources for use, the latter concept being restricted only to resources that can be exploited. Therefore, an indicator that describes higher efforts addresses the scarcity of resources rather than their depletion and is therefore considered relevant for stakeholders to evaluate medium-term policies (Vieira et al. 2011). Hauschild et al. (2013) take a step further by identifying the scarcity of the resource, i.e., the limitations in its availability to current and future generations, as the key concern for the resources impact category in LCIA.

Quantifying the impact of a product's life cycle on the economy, also known as monetisation, by using the willingness-to-pay concept has been applied in the past (Steen 1999; Weidema 2009). For resource use, however, the willingness-to-pay concept is not related to the effect of resource production, but rather to the willingness to make additional investments for resource production (Li et al. 2009). Here, we propose a method to assess the impact on fossil resource scarcity in LCA based on surplus cost, which is the global future cost increase due to marginal fossil resource use. This indicator, which has been applied in the ReCiPe method (Goedkoop and De Schryver 2009), was selected by the EC-JRC-IES (2011) as an interim solution at the endpoint level. It was considered as the most relevant method but still too immature for recommendation.

The goal of this paper was to develop a life cycle impact assessment method for the scarcity of fossil resources based on future societal costs. Current methods expressed as surplus cost only provide data for a limited number of fossil resources (crude oil), assume constant annual production over time, use limited price–production relationships and set an arbitrary time frame (Goedkoop and De Schryver 2009). Characterization factors for the three main fossil resources (crude oil, natural gas and coal) were derived to overcome these limitations and demonstrate how the method can be operated in practice.

2 Methods and data

2.1 Cause–effect pathway

The largest part of a fossil resource is combusted for energy production (about 94 % in 2010; IHS 2011), either directly or via a conversion/purification step. The remaining part is used for its chemical properties in plastics and other synthetic materials. To express the scarcity of a fossil resource, we propose to use an economic indicator as scarcity is best expressed in economic terms (Tilton 2003). The cause–effect pathway of the indicator proposed here is illustrated in Fig. 1.

It is assumed that fossil fuels with the lowest costs are extracted first. Consequently, the increase in fossil fuel production causes an increase in costs due to either a change in production technique or sourcing from a costlier location. For example, when all conventional oil is depleted, alternative techniques such as enhanced oil recovery will be applied or oil will be produced in alternative geographical locations with higher costs, such as arctic regions (IEA 2010). The additional production cost indicator is defined here as the marginal cost

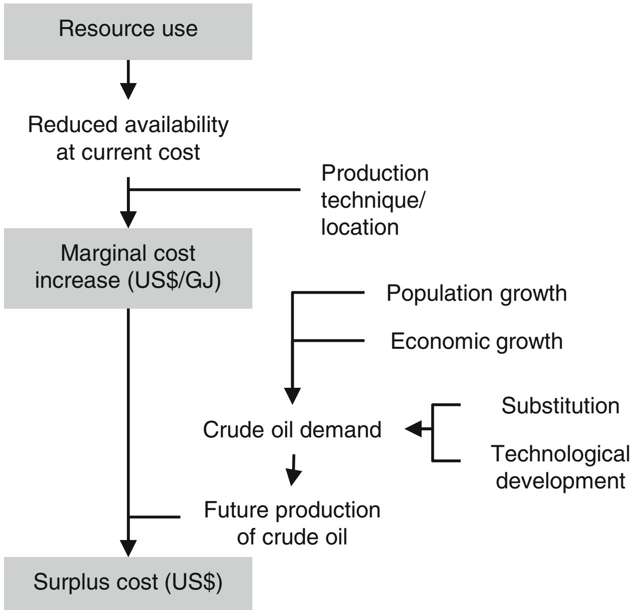

Fig. 1 Pathways of fossil resource use to the damage indicator

increase (MCI), which is the cost of the additional inputs needed to produce another unit of the resource. By combining the marginal cost increase with a production volume of the fossil resource consumed, the additional cost for that production, due to a currently produced amount, is derived. Weidema et al. (2005) suggested including this mechanism in the inventory instead of in the impact assessment step. However, this has not yet been done and life cycle inventory databases still express the resource use elementary flows as the amount of primary resource extracted. As such, we propose a life cycle impact indicator, expressed as the surplus cost (SC) caused by fossil resource scarcity, which is expressed as the total additional future cost to the global society due to the production of one extra unit of resource now. Thus, the SC scales with the future global production, which can be forecasted in different scenarios by simulating demand related to assumptions on population growth, economic growth, substitution of resources, and expected technological development (IPCC 2000).

2.2 Characterisation factors

The calculation of marginal change is common in LCIA (Udo de Haes et al. 1999). For resources, this concept implies that each additional extraction of a resource causes future impact on the scarcity of the resource in nature. The factor quantifying the change that is caused by an extraction from nature is referred to as the characterization factor (CF) of the resource considered. Here, the CF is equal to the surplus cost of fossil resource × (SC_x; US dollars per kilogram or cubic metre). As explained in the previous section, it is related to the MCI combined with a future production volume. However, future costs may be valued less in terms of present value due to expected discount rates (this will be explained further in Section 2.4). The equation for calculating the CF is then

$$CF_x = SC_x = \sum_{t=1}^{T}\left(MCI_x \times P_{x,t} \times \frac{1}{(1+d)^t}\right) \tag{1}$$

where MCI_x is the marginal cost increase of the fossil resource x, $P_{x,t}$ is the annual production of resource x in year t counting from the base year, T is the year in which resource x is depleted, and d is the discount rate. T is derived by calculating, on basis of energy demand estimates, how long it will take until the total resources are depleted, as reported by IEA (2010). The costs are expressed in US dollars in the year 2008. When cost is expressed for a different year, the cost is corrected for inflation, using the average of the past 30 years in the USA (3 %).

The MCI of resource x (in US dollars in the year 2008 per squared kilogram or US dollars in the year 2008 per cubic metre squared), defined as an intermediate parameter for calculating the CF, is defined as the extra cost resulting from the production of one additional kilogram or cubic metre of fossil fuel and is calculated by

$$MCI_x = \frac{\Delta Cost_x}{\Delta P_x} \tag{2}$$

where $\Delta Cost_x$ is the change in cost per kilogram or cubic metre of resource x (US dollars in the year 2008 per kilogram or US dollars in the year 2008 per cubic metre) and ΔP_x is the change in amount of resource to be produced in the future (kilogram or cubic metre). The MCI is based on current cost estimates per region and production type (source type, production technique). Amounts of fossil resources (kilogram or cubic metre) can be converted to heating values (megajoule), thus allowing the comparison of CFs between types of fossil resources on the basis of each heating value. As the mass or volume of a fossil resource is generally corrected based on the lower heating value (LHV), we used the following conversion rules: 1 kg of crude oil equivalent has an LHV of 41.868 MJ, 1 kg of coal equivalent has an LHV of 0.7 * 41.868= 29.3076 MJ, and a cubic metre of natural gas has an LHV of 38 MJ at 15 °C and 1,013 hPa (IEA 2011b). When a data source uses barrels of oil equivalents (159 l), we assume a density of 0.85 kg per litre (135 kg per barrel).

2.3 Cost–cumulative production data

Cost–cumulative production data of crude oil, natural gas and coal are required for calculating the MCIs, where cumulative production means the increasing future production of successive available resource per production technique or region. The resources of these fossil fuels, as published by the

International Energy Agency (IEA 2010), are used. According to IEA (2010), the resources estimate comprises three parts: proven reserves, undiscovered resources and “reserves growth”.

2.3.1 Crude oil

Crude oil is found in ancient sea or lake bottoms, where organic materials were buried under anoxic conditions and became fossilised. Hence, crude oil sources can be found in diverse locations at different depths underground and under existing sea or lake bottoms. Due to the variation in source locations, the cost is highly diverse. Crude oil can have different densities and can be mixed with sediments, which also has consequences on the production costs. In certain oil reservoirs, enhanced oil recovery (EOR) techniques are required to extract the remaining resources that cannot be recovered in a conventional way. These techniques are only applied when the oil prices increase to levels that make them profitable.

Future production cost of crude oil was estimated per production technique by the International Energy Agency (IEA 2010). The IEA cost data includes all capital expenditure, operational expenditure, and cost of capital to bring the oil to the market, but does not include any return on investment (McGlade 2011). The IEA cost data are given in ranges per production technique, but are not specified per region (except for—Middle East and North Africa (MENA)—conventional oil) as illustrated in Fig. 2.

2.3.2 Natural gas

Natural gas mainly consists of methane and, like crude oil, originates from marine organisms. It is found either in association with crude oil or in isolated natural gas fields. As natural gas prices are increasing, industry is producing natural gas from increasingly more challenging types, such as tight gas, shale gas, and sour gas, and from more challenging locations, such as arctic, deep water, and coal beds. In IEA (2009a), cost–cumulative production data is given in ranges per production technique (Fig. 3).

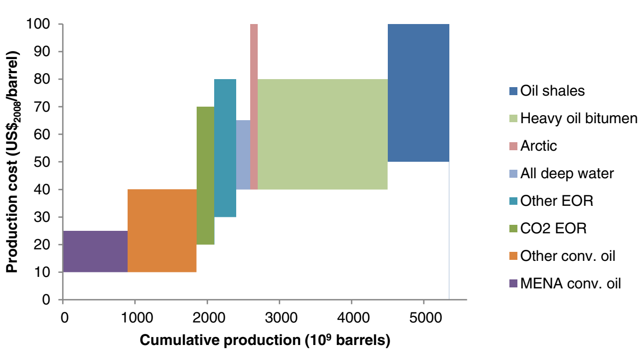

Fig. 2 Cost–cumulative production data for crude oil. A barrel (of oil equivalents) contains 159 l assuming a density of 0.85 kg per litre (135 kg per barrel). *EOR* enhanced oil recovery; *conv.* conventional; *MENA* the Middle East and North Africa region (source: IEA 2010)

2.3.3 Coal

Coal was formed from forest biomass, which was buried in the ground or shallow seas mainly during the carboniferous period (360–300 million years ago). Due to plate tectonics and other geologic processes, coal is found at different depths underground. Because these geological processes apply pressure to the buried biomass, there is a large variation in carbon content, which is used in the German classification of different coal types, e.g., lignite has 60–75 % C, flame coal has 75–82 % C, etc.

The IEA has not published cost–cumulative production data per production technique for coal. IEA’s total estimate for coal resources is based on data collected by the German Federal Institute for Geosciences and Natural Resources (BGR 2010). These data of coal resources are specified per country, but not per production technique. In BGR (2010), coal resources are divided into two types: lignite (including sub-bituminous) and hard coal (including anthracite).

Cost data are not available for all types of coal. Data for free-on-board cash cost (costs include mining, processing, taxes and royalties, inland transport and port and loading, but not covering overhead costs or capital costs) of seaborne-traded steam coal production are available per country. We assumed the same cost for all types of coal per metric tonne of coal equivalent (adjusted to 29.3 MJ per kg). Cost data were taken from IEA (2011a) for Canada, USA, Russia, Mongolia, Indonesia, Australia, and IEA (2009b) for China (Fig. 4). For Ukraine, Germany, Kazakhstan, Poland and the UK (together about 3 % of total available resources) and for Pakistan, Vietnam and India (4 % of total available resources), there are no cost data. Other countries do not have significant amounts of

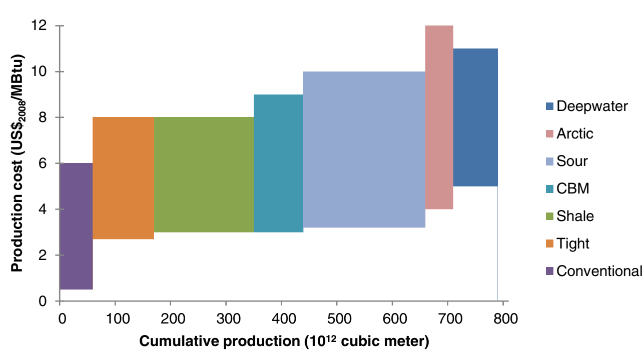

Fig. 3 Cost–cumulative production data for natural gas. MBtu is 10^6 Btu, where 1 MBtu=1.054615 GJ. *CBM* coal bed methane (source: IEA 2009a)

resources (<0.05 10^{-15} kg), according to BGR (2010) data. The data used in this paper are illustrated in Fig. 4.

2.3.4 Data analysis

To derive a slope from the minimum and maximum cost per production technique or country, a certain statistical distribution had to be assumed. Monte Carlo simulations were applied assuming a uniform distribution between the minima and maxima per production technique or country. Simulations were done for equal quantities of available resource with the condition that the second digit of the slope, which is derived by linear regression after ordering the cost values from lowest to highest, did not change: 10^7 barrels for crude oil, 10^{10} cubic metres for natural gas, and $2 \cdot 10^8$ metric tonnes for coal. For the Monte Carlo simulations and the linear regressions, the R-project statistical software (R Development Core Team 2012) was used.

2.4 Discount rates and global future production data

Because the method proposed aims at quantifying the potential additional cost in future fossil fuel production as a result of current production, value choices to define future scenarios had to be made. In LCIA, it is possible to define different perspectives, representing different visions on nature and on society, following the Cultural Theory (Hofstetter 1998; Frischknecht et al. 2000; Goedkoop et al. 2008). Three of the five Cultural Theory perspectives, the individualist, hierarchist, and egalitarian, are generally applied in environmental decision tools when perspectives are considered (Hofstetter 1998; Hofstetter et al. 2000). The autonomist is excluded because he/she "escapes social control by refusing to control or to be controlled by other" and fatalists do not choose but follow the others (Hofstetter 1998). Therefore, these are not relevant perspectives for decision making tools, such as LCA.

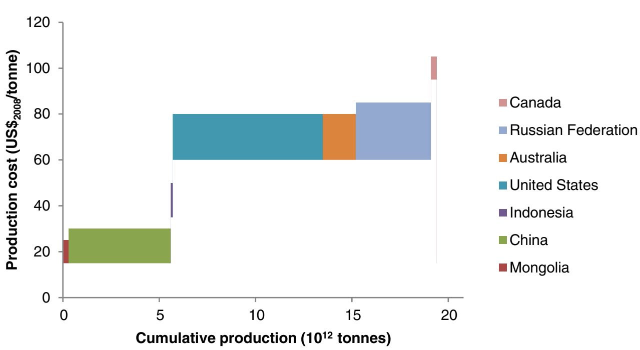

Fig. 4 Cost–cumulative production data for coal adjusted to 25.1 MJ per kg; about 7 % of the total available resources are not included due to lacking cost data for several countries (sources: BGR 2010; IEA 2009b; IEA 2011a)

As using a fixed timeframe is not a common practice in future economic cost assessments, such as in cost–benefit analyses and life cycle costing, we did not apply it for calculating the surplus cost. Moreover, using a fixed timeframe would make the surplus cost characterisation factors even more sensitive to the future production scenarios. Discounting future costs can be applied, but it is a subjective choice, as it assumes that costs in the future can be compensated by investing money in profitable projects or by keeping money in a savings account with stable interest rates. Discount rates for estimating future environmental cost are generally between 1 and 7 % (Hof et al. 2008; Harrison 2010).

Choosing different discount rates per perspective for the use in LCIA has often been applied (Hellweg et al. 2003). For example, De Schryver et al. (2011) applied zero discounting for the egalitarian perspective, 3 % discount rate for the hierarchist perspective, and 5 % discount rate for the individualist perspective. Discounting of zero for the egalitarian and 3 % for the hierarchist perspective is consistent with, respectively, the long-term (indefinite) and medium-term (100 years) time frame often considered in LCIA. The individualist perspective is typified with a short-term perception, not longer than 20 years. Applying a 5 % discount rate, as De Schryver et al. (2011) suggest, is not in line with this time frame. A discount rate of higher than 10 %, as used by private companies (Hellweg et al. 2003), is more appropriate for a short-term individualist perception. Moreover, a 15 % discount rate for the individualist and 3 % for the hierarchist perspective would result in a similar ratio between the characterisation factors of the two perspectives in case fixed time frames of 20 and 100 years, respectively, are used. As fixed timeframes are often used for other impact categories, such as climate change, this makes the surplus cost method compatible with those categories. We therefore chose a discount rate of 15 % for the individualist, 3 % for the hierarchist and zero discounting for the egalitarian perspective.

In the case of the egalitarian perspective with zero discounting, the future production scenarios do not have any influence on the results because all future production needs to be taken into account and is considered equally important. In the cases of the hierarchist and the individualist perspectives, however, fossil production scenarios of the coming decades are very relevant due to positive discounting. Many future production scenarios can be simulated depending on the macro-economic model and underlying assumptions. The Intergovernmental Panel on Climate Change (IPCC) (2000) published four different scenario groups, known as the Special Report on Emissions Scenarios (SRES), which were applied by six different macro-economic models. We used the annual primary energy production scenarios from all models.

When comparing the SRES scenario groups (IPCC 2000) and the three cultural perspectives used in LCA (Hofstetter 1998), the storyline of the scenario group A1

matches most closely to the description of the individualist perspective (Beumer and Martens 2010). For example, in both the scenario narrative and the individualist perspective, economic growth is seen as the main driver of development and technological innovation makes resources more accessible (Beumer and Martens 2010). For the other scenario groups, it is not that obvious which perspective is predominantly represented (Beumer and Martens 2010). On the other hand, we observe a clear trend in fossil resource production in scenario group B1 that can clearly be described as "low growth (radical change now)", which is the (fossil) 'energy future' prediction of the egalitarian. Moreover, the fossil resource production trend in scenario B2 can clearly be described as "middle of the road", which is the "energy future" prediction of the hierarchist. Moreover, Kapur (2005) came to the same match in his analysis.

To assess the uncertainty of the surplus cost, Monte Carlo simulations were applied with the minima and maxima of the annual production from the different IPCC models (assuming uniform distribution).

3 Results and discussion

3.1 Marginal cost increase

In Fig. 5, a statistical overview is given of the MCI results obtained in 10^{-18} US$_{2008}$ per MJ^2. The individual charts and the MCI results in 10^{-18} US$_{2008}$ per MJ^2 and 10^{-15} US$_{2008}$ per kg^2 (or US dollars in the year 2008 per m^6 for natural gas) are available in the Supplementary Material. From this overview, it is clear that the MCIs of the different types of fossil fuels are significantly different, where the MCI of crude oil is about two times as high as the MCI of natural gas and a factor 100 higher than the MCI of coal.

For comparison, we estimated slopes from cost–cumulative production curves in literature. The slope for crude oil

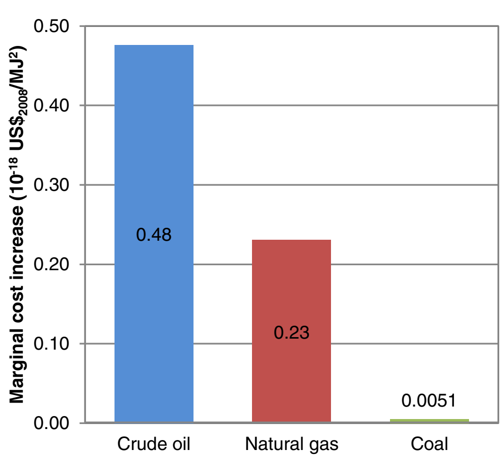

Fig. 5 Overview of the MCI results

retrieved from data in Remme et al. (2007) and in Anandarajah et al. (2011) are approximately 0.40 10^{-18} and 0.57 10^{-18} US$_{2008}$/MJ^2, respectively. The reason for the difference between Anandarajah et al. (2011) and our estimates based on the Monte Carlo simulations with the IEA data is mainly due to the difference in available resources per production technique (their sum of available resource is about $3{,}800 \cdot 10^9$ barrels compared to $5{,}300 \cdot 10^9$ barrels, respectively). Their cost estimates are largely based on the IEA data as well. Remme et al. (2007), McGlade (2011) and Anandarajah et al. (2011) specified cost data per production type and region by literature review (partly based on IEA data), rather than an assumed distribution between the minimum and maximum costs.

Compared to BGR (2010) estimates of natural gas resources, the IEA (2009a) estimates are about 30 % smaller (IEA's sum estimate of conventional, tight gas, shale gas, coal bed methane and sour gas resources is 790 trillion cubic metre, compared to 1,151 of BGR). This means that the slope (MCI) would be about 30 % lower when BGR (2010) data for natural gas resources are used. Moreover, IEA (2009a) estimates do not include aquifer gas and gas hydrates as BGR (2010) does. BGR estimates the resources of aquifer gas and gas hydrates at respectively 800 and 1000 trillion cubic metres. The cost estimates of producing these types of gas would therefore strongly influence the results of calculating the MCI of natural gas.

Based on Remme et al. (2007), we estimate an MCI of 0.21 10^{-18} US$_{2008}$/MJ^2 by drawing a line through their cost–cumulative production curve. From Anandarajah et al. (2011), we estimate an MCI of 0.33 10^{-18} US$_{2008}$/MJ^2 in the same way. The latter estimate is much higher than our estimate mainly because the total resource estimate of Anandarajah et al. (2011) is smaller, which makes the slope (MCI) steeper because they used a similar cost range.

As stated in the methods and data section, about 7 % of the total available coal resources are not included due to lack of cost data for several countries. Because the cost ranges in those countries are probably not higher than those of the included countries, the result may be slightly overestimated.

In Fig. 4, the discontinuity of the curve is rather prominent around $6 \cdot 10^{15}$ kg and towards $19 \cdot 10^{15}$ kg. This means that, in theory, the production cost will steeply increase when those amounts of cumulative production are reached in the future. In practice, there will be a smoother transition as lower cost mines will produce at the same time as higher cost mines, of which the owners accept lower margins and/or receive subsidies (IEA 2012). It should be noted, however, that the relative contribution per country to total available resources as used in our analysis is very different from the relative contribution to the current production (for example, based on BGR (2010)), China produced 44 % of the global coal production in 2009 and has 25 % of the total reserves, while the USA produced

14 % and has 38 % of the reserves. This means that if we would use average costs in the first 100 years or so, based on the current relative production per country, for calculating the MCI of coal, the slope would be more moderate. However, this involves predictions of future annual production per country for the coming centuries, which are unavailable.

The cost of coal production is estimated by Remme et al. (2007) between 1 and 4.8 US$$_{2000}$ per GJ, which is equal to 0.034 and 0.164 or 0.043 and 0.21 US$$_{2008}$/kg coal eq., when applying an inflation rate of 3 % to convert the cost to the reference year of 2008. The total available resources estimate in Remme et al. (2007) is not comparable, though they also refer to BGR as the data source.

3.2 Characterisation factors

Figure 6 gives an overview of the characterisation factors calculated for crude oil, natural gas and coal according to the three cultural perspectives selected. The CF results in US dollars in the year 2008 per gigajoule and US dollars in the year 2008 per kilogram (or US dollars in the year 2008 per cubic metre for natural gas) are available in the Supplementary Material. The characterization factors for the egalitarian perspective are 14.3, 6.8, and 3.2 US$$_{2008}$ per GJ for crude oil, natural gas and coal, respectively. These factors are relatively high because for this perspective, we do not use discounting and assume all resources are eventually depleted. In the individualist and hierarchist perspectives, the average characterisation factors are much lower, but discounting makes the results sensitive to the future production scenarios, as simulated by the different models in IPCC (2000). The CF ratios crude oil/natural gas is rather constant, while the relative importance of coal largely differs between the perspectives. Coal has a much higher relative importance in the egalitarian perspective than in the other perspectives because coal production is expected to continue for much longer than natural gas and crude oil.

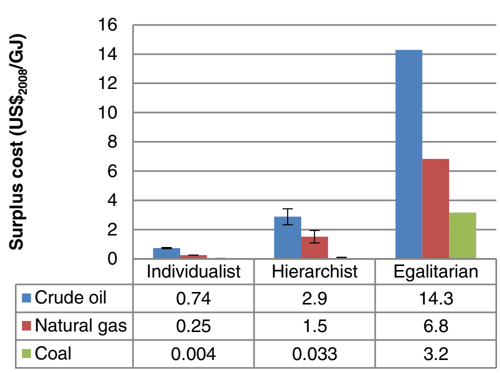

Fig. 6 Average and standard deviation of the surplus cost in US$$_{2008}$ per GJ fossil fuel for different perspectives using fossil fuel production simulated by six different models (IPCC 2000) and two different scenarios (assuming *A1* individualist; *B2* hierarchist)

3.3 General discussion

Fossil resource production costs values used in this paper are based on recent estimates, while actual costs fluctuate depending on inflation rates, local wage policies, fuel prices, and other national and international economic parameters. Because the breakdown of cost per production technique and region can differ significantly, the cost fluctuations can have a large influence on the marginal cost increase calculation. As there are also differences in the breakdown of cost per type of fossil resource, the fluctuations can also lead to relative differences between the fossil resource types. This effect was not investigated due to lack of specific data. State-of-the-art data published by IEA (2010) was used. However, if new data becomes available in the future, the characterisation factors can be easily updated.

A basic assumption of our method is that the least costly production techniques are used first. However, this is not always the case due to geopolitical factors such as trade barriers or strategic stocking of resources. For example, some countries have recently decided to start exploiting shale gas despite the high costs and risks involved. Including such effects would involve a large degree of additional uncertainty to the assessment and a necessity for spatial differentiation. It would also implicate a very short term perspective (less than 5 years), as geopolitical effects may change rapidly. Most importantly, there is lack of data and this is why the method proposed has focused primarily on technological factors and demand growth.

When calculating the characterization factors, the ratio between the CF of crude oil/natural gas/coal, in general, does not change much compared to the MCI (100:48:1.1). This means that the calculations from the MCI to the CFs are, in most cases, insensitive to the subjective choices. In the hierarchist perspective, the ratio becomes 100:52:1.1. In the individualist perspective, the ratio becomes 100:34:0.6. In the egalitarian perspective, the ratio becomes 100:48:22, which deviates significantly for coal due to the zero discounting in this perspective and the expectation that coal reserves can be produced for centuries. The small relative difference between the individualist and hierarchist perspectives means that there is not much difference in the importance of the different types of fossil resources between the perspectives. Only in the egalitarian perspective is the characterisation factor of coal relatively much larger compared to the other perspectives, though it is still a factor of five lower than the CF of crude oil. This means that the economic impact caused by resource scarcity in terms of surplus cost can be reduced considerably, independently of the perspective, by switching to coal use. The trade-off is obviously an increased impact on global

warming, as coal releases more CO_2 per MJ than crude oil or natural gas.

In absolute terms, there is a significant difference between the perspectives. The individualist perspective, although not necessarily compatible with the thinking that all impacts should be fully considered, represents an important stakeholder group that has to understand, interpret, and use LCA results. This could be considered a minimum damage approach. As a result, the surplus cost for this perspective is lowest and only a fraction compared to the current price of fossil resources. As a reference, the current prices are approximately 17, 5, and 4.5 US$_{2008}$ per GJ for crude oil, natural gas and coal, respectively, which means the individualist CFs are about 4, 5 and 0.1 % of the current price. In the hierarchist, and especially in the egalitarian perspective, the surplus cost is a significant amount compared to the current price of crude oil and natural gas. The surplus cost of coal use is only significant compared to the current price in the egalitarian perspective.

Stakeholders (oil/natural gas and other industry representatives, policy makers and scientists) expressed their doubts on the relevance of a fossil resource scarcity indicator because concern for climate change is currently a driving substitution of fossil resources (Vieira et al. 2011). A comparison with the social cost of carbon can give an idea of the relevance of fossil resource scarcity according to our calculations. The average peer-reviewed social cost of carbon is 43 US$_{2000}$ (54 US$_{2008}$) per metric tonne of carbon with a standard deviation of 83 US$_{2000}$ (105 US$_{2008}$) (Yohe et al. 2007). This can be converted using atomic weights into 14.9 US$_{2008}$ average social cost per metric tonne of carbon dioxide. Gómez et al. (2006) reported default emission factors of 0.073, 0.056 and 0.095 metric tonnes of carbon dioxide per gigajoule of crude oil, natural gas and coal combusted, respectively. Combined, this results in social costs per calorific value of 1.1, 0.8 and 1.3 US$_{2008}$ per GJ of crude oil, natural gas and coal, respectively. These are in the same order of magnitude as the surplus costs in the individualist and hierarchist perspectives for crude oil (0.74–2.9 US$_{2008}$ per GJ) and natural gas (0.25–1.5 US$_{2008}$ per GJ) and a much higher value in those perspectives for coal (0.004–0.033 US$_{2008}$ per GJ). Compared to the surplus cost values in the egalitarian perspective (3.2–14.3 US$_{2008}$ per GJ), the social cost values are considerably lower.

From the individualist perspective, which assumes we can manage needs and resources, low characterization factors fit. Individualists are not particularly concerned about resource availability as they have a dominantly short-term perception of time (5 to 20 years). The extremely high characterization factors are appropriate for the egalitarian perspective, which has a dominantly long-term perception of time and is very concerned about resource availability for future generations (Hofstetter 1998). The characterization factors for the hierarchist perspective are typically in between those of the other two perspectives, though nearer to the individualist.

The surplus cost can be considered an impact indicator at endpoint (damage) level, but we did not find a common indicator for crude oil, natural gas and coal at midpoint level. The reason for this is that there is no common pathway at any point before the surplus cost, as illustrated in Fig. 1. Jolliet et al. (2004) recognised that in some cases of modelling at damage level, pathways could be better modelled without involving indicators at midpoint level.

4 Conclusions

Characterisation factors were calculated for the primary fossil resources crude oil, natural gas and coal, expressed per mass or volume equivalents based on the lower heating value, which can be directly used for impact assessment in LCA. We further developed a life cycle impact assessment method for resource scarcity of crude oil, natural gas and coal, in which the marginal cost increase is calculated as an intermediate parameter and surplus cost is calculated for three perspectives—individualist, hierarchist and egalitarian—as an impact indicator. For other types of non-renewable resources, in particular minerals, a similar method can also be applied and is currently under development. This will result in multiple impact categories following a similar cause–effect pathway, which can then be aggregated in the safeguard subject Natural resources. When expressing the characterisation factors per gigajoule, the impacts are highest for crude oil and lowest for coal. The impact of natural gas in all perspectives is about half of the impact of crude oil. The impact of coal is generally a factor of 100 lower compared to crude oil. Only in the egalitarian perspective, where no discounting is applied, the impact of coal is only a factor of five lower.

Acknowledgments The research was funded by the European Commission under the 7th framework programme on environment; ENV.2009.3.3.2.1: LC-IMPACT - Improved Life Cycle Impact Assessment methods (LCIA) for better sustainability assessment of technologies, grant agreement number 243827. We thank Mark Huijbregts (Radboud University Nijmegen) for his valuable feedback on draft versions of this manuscript.

References

Anandarajah G, Pye S, Usher W, Kesicki F, McGlade C (2011) TIAM-UCL Global model documentation. Working Paper. February 2011: REF UKERC/WP/ESY/2011/001. University College London

Bentley RW (2002) Global oil and gas depletion: an overview. Energy Policy 30(3):189–205

Berger M, Finkbeiner M (2011) Correlation analysis of life cycle impact assessment indicators measuring resource use. Int J Life Cycle Assess 16(1):74–81

Beumer C, Martens P (2010) Noah's ark or World Wild Web? Cultural perspectives in global scenario studies and their function for

biodiversity conservation in a changing world. Sustainability 2(10): 3211–3238

BGR (2010) Reserves, resources and availability of energy resources. Annual report 2010. Federal Institute for Geosciences and Natural Resources (BGR)

De Schryver AM, Van Zelm R, Humbert S, Pfister S, McKone TE, Huijbregts MAJ (2011) Value choices in life cycle impact assessment of stressors causing human health damage. J Ind Ecol 15(5): 796–815

EC-JRC-IES (2011) International Reference Life Cycle Data System (ILCD) handbook—recommendations for life cycle impact assessment in the European context. First edition November 2011. European Commission-Joint Research Centre - Institute for Environment and Sustainability. Luxemburg. lct.jrc.ec.europa.eu/pdf-directory/Recommendation-of-methods-for-LCIA-def.pdf

Finnveden G (2005) The resource debate needs to continue. Int J Life Cycle Assess 10(5):372

Frischknecht R, Braunschweig A, Hofstetter P, Suter P (2000) Human health damages due to ionising radiation in life cycle impact assessment. Environ Impact Assess 20(2):159–189

Goedkoop M, De Schryver A (2009) Fossil Resource. Chapter 13 in. Goedkoop M, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, Van Zelm R (eds) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation factors, first edition

Goedkoop M, Heijungs R, Huijbregts M, De Schryver AM, Struijs J, Van Zelm R (2008) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I. Characterisation. Den Haag, The Netherlands, VROM

Gómez DR, Watterson JD, Americano BB, Ha C, Marland G, Matsika E, Namayanga LN, Osman-Elasha B, Saka JDK, Treanton K (2006) Stationery combustion, Chapter 2. Energy, Volume 2. In: IPCC (eds) 2006 IPCC Guidelines for National Greenhouse Gas Inventories

Guinée JB (ed), Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, Van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, De Bruijn JA, Van Duin R, Huijbregts MAJ (2002) Handbook on life cycle assessment: operational guide to the ISO standards. Series: eco-efficiency in industry and science. Kluwer Academic Publishers. Dordrecht (Hardbound, ISBN 1-4020-0228-9; Paperback, ISBN 1-4020-0557-1)

Harrison M (2010) Valuing the future: the social discount rate in cost-benefit analysis, Visiting Researcher Paper. Productivity Commission, Canberra

Hauschild M, Potting J (2005) Spatial differentiation in life cycle impact assessment—the EDIP2003 methodology. Environmental News no. 80. The Danish Ministry of the Environment, Environmental Protection Agency, Copenhagen

Hauschild MZ, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O, Margni M, De Schryver A, Humbert S, Laurent A, Sala S, Pant R (2013) Identifying best existing practice for characterization modeling in life cycle impact assessment. Int J Life Cycle Assess 18:683–697

Hellweg S, Hofstetter TB, Hungerbiihler K (2003) Discounting and the environment: should current impacts be weighted differently than impacts harming future generations? Int J Life Cycle Assess 8(1):8–18

Hof AF, den Elzen MGJ, van Vuuren DP (2008) Analysing the costs and benefits of climate policy: value judgements and scientific uncertainties. Glob Environ Chang 18(3):412–424

Hofstetter P (1998) Perspectives in life cycle impact assessment, a structure approach to combine models of the technosphere, ecosphere and valuesphere. Kluwer Academic Publishers, Dordrecht, The Netherlands, p 484

Hofstetter P, Baumgartner T, Scholz RW (2000) Modelling the valuesphere and the ecosphere: integrating the decision makers' perspectives into life cycle assessment. Int J Life Cycle Assess 5: 161–175

Huijbregts MAJ, Hellweg S, Frischknecht R, Hungerbühler K, Jan Hendriks A (2008) Ecological footprint accounting in the life cycle assessment of products. Ecol Econ 64(4):798–807

IEA (2009a) World energy outlook 2009. OECD/IEA, Paris, France

IEA (2009b) Cleaner coal in China. OECD/IEA, Paris, France

IEA (2010) Resources to Reserves 2010. Oil, gas and coal technologies for the energy markets of the future. To be released Autumn 2010

IEA (2011a) Coal. Medium-term market report 2011. Market trends and projections to 2016. IEA, Paris, France

IEA (2011b) Key world energy statistics

IEA (2012) World energy outlook 2012. OECD/IEA, Paris, France

IHS (2011) Petrochemical Industry Overview. http://www.ihs.com/products/chemical/planning/ceh/petrochemical-industry.aspx Accessed April 2011

IPCC (2000) Emission scenarios. A special report of the IPCC working group III

Jackson T, Papathanasopoulou E (2008) Luxury or 'lock-in'? An exploration of unsustainable consumption in the UK: 1968 to 2000. Ecol Econ 68(1–2):80–95

Jolliet O, Müller-Wenk R, Bare J, Brent A, Goedkoop M, Heijungs R, Itsubo N, Peña C, Pennington D, Potting J, Rebitzer G, Stewart M, De Haes HU, Weidema B (2004) The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. Int J Life Cycle Assess 9(6):394–404

Kapur A (2005) The future of red metal—scenario analysis. Futures 37(10):1067–1094

Lenzen M, Dey C, Foran B (2004) Energy requirements of Sydney households. Ecol Econ 49(3):375–399

Li H, Jenkins-Smith HC, Silva CL, Berrens RP, Herron KG (2009) Public support for reducing US reliance on fossil fuels: Investigating household willingness-to-pay for energy research and development. Ecol Econ 68(3):731–742

Lindeijer E, Müller-Wenk R, Steen B (2002) Impact assessment of resources and land use. In: Udo de Haes HA, Finnveden G, Goedkoop M, Hauschild M, Hertwich EG, Hofstetter P, Jolliet O, Klöpffer W, Krewitt W, Lindeijer EW, Müller-Wenk R, Olsen SI, Pennington DW, Potting J, Steen B (eds) Life-Cycle Impact Assessment: Striving towards best practice. SETAC-Press, Pensacola

McGlade C (2011) Uncertainties in the long term availability of crude oil. 34th IAEE International Conference Proceedings. http://www.hhs.se/IAEE-2011/Program/ConcurrentSessions/Documents/1%20online%20procedings/2147228%20Uncertainties%20in%20the%20long%20term%20availability%20of%20crude%20oil.pdf. Accessed 10 April 2012

Müller-Wenk R (1998) Depletion of abiotic resources weighted on base of "virtual" impacts of lower grade deposits used in future. IWO- Diskussionsbeitrag nr. 57. ISBN-Nr. 3-906502-57-0

R Development Core Team (2012) R: a language and environment for statistical computing, version 2.11.1 (2010-05-31). R Foundation for Statistical Computing: Vienna, Austria, 2012; http://www.R-project.org

Remme U, Blesl M, Fahl U (2007) Global resources and energy trade: an overview for coal, natural gas, oil and uranium. Universität Stuttgart. Institut für Energiewirtschaft und Rationelle Energieanwendung

Schneider L, Berger M, Finkbeiner M (2011) The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources. Int J Life Cycle Assess 16(9):929–936

Steen B (1999) A systematic approach to environmental priority strategies in product development (EPS). Version 2000 – Models and data

of the default method. CPM report 1999:5. Chalmers University of Technology, Environmental Systems Analysis

Steen BA (2006) Abiotic resource depletion: different perceptions of the problem with mineral deposits. Int J Life Cycle Assess 11(1):49–54

Stewart M, Weidema BA (2005) Consistent framework for assessing the impacts from resource use: a focus on resource functionality. Int J Life Cycle Assess 10(4):240–247

Tilton JE (2003) On borrowed time? Assessing the threat of mineral depletion. Resources for the Future, Washington

Udo de Haes H, Jolliet O, Finnveden G, Hauschild M, Krewitt W, Müller-Wenk R (1999) Best available practice regarding impact categories and category indicators in life cycle impact assessment. Int J Life Cycle Assess 4(2):66–74

Van der Voet E (2013) Criticality and abiotic resource depletion in life cycle assessment. Chapter 5. In: Mancini L, De Camillis C, Pennington D (eds) Security of supply and scarcity of raw materials: towards a methodological framework for sustainability assessment. European Commission, Luxemburg

Vieira M, Storm P, Goedkoop M (2011) Stakeholder consultation: what do decision makers in public policy and industry want to know regarding abiotic resource use? In: Finkbeiner M (ed) Towards life cycle sustainability management. Springer, Dordrecht Heidelberg London New York

Weidema BP (2009) Using the budget constraint to monetarise impact assessment results. Ecol Econ 68(6):1591–1598

Weidema B, Finnveden G, Stewart M (2005) Impacts from resource use: a common position paper. Int J Life Cycle Assess 10(6):382

Yohe GW, Lasco RD, Ahmad QK, Arnell NW, Cohen SJ, Hope C, Janetos AC, Perez RT (2007) Perspectives on climate change and sustainability. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp 811–841